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Dilution of boundary layer cloud condensation nucleus concentrations by free tropospheric entrainment during marine cold air outbreaks

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Mid-latitude marine cold air outbreaks (CAOs) occur in the post-frontal sector of extratropical cyclones. Once advected over the ocean, the marine boundary layer (MBL) quickly deepens and hosts near-overcast clouds that transition into an open-cellular cloud field downwind, mediated by a reduction in aerosol concentrations. Typically, the MBL experiences strong large-scale subsidence that is often associated with free-tropospheric (FT) dry intrusions. Apart from being relatively warm and dry, FT air may have substantially different aerosol properties and, thus, different cloud condensation nuclei (CCN) concentrations compared to the MBL.

In this study, we examine the difference between MBL and FT air by using in-situ and remote sensing observations collected during NASA's ACTIVATE (Aerosol Cloud Meteorology Interactions over the Western Atlantic Experiment) field campaign in the northwest Atlantic. Analysis of the 8 CAO flights in 2020 reveals predominantly far lesser CCN concentrations in the FT than in the MBL. We investigate one representative flight more deeply, through a fetch-dependent MBL CCN budget that has contributions from sea-surface fluxes, hydrometeor collision-coalescence, and entrainment of FT air. We find a dominant role of FT entrainment in reducing MBL CCN concentrations upwind of strong precipitation that results in cloud regime transition, consistent with satellite-retrieved gradients in droplet number concentration upwind of precipitation.

The FT circulation and its relative lack of CCN can accelerate overcast-to-broken cloud transitions, especially where MBL air is CCN-rich (e.g., near continents), and thereby dramatically reduce regional albedo.